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**AUTOMATIC SHIELD CONTROL FOR A
MODERATE TEMPERATURE ADIABATIC
CALORIMETER**

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THESIS

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TEMPERATURE ADIABATIC CALORIMETER

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Herbert Weldon Head

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Automatic Shield Control for a Moderate
Temperature Adiabatic Calorimeter

by

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ABSTRACT

An automatic, electronic controller was designed for use with adiabatic calorimeters. The controller employed reset action, and its behavior at different system gains was analyzed using the analytic techniques of feedback control theory. In accord with the analysis satisfactory performance was obtained with a calorimeter characterized by large thermal lags, but marginal performance was obtained with another calorimeter characterized by a rapid thermal response. A second controller, which employs reset and proportional action gave satisfactory results during preliminary testing for both calorimeters.

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I. INTRODUCTION

When thermodynamic measurements are made in an adiabatic calorimeter, the heat exchange between the sample and its enclosure should be zero. To accomplish this goal, it is necessary to observe and control the temperature difference between the sample and its enclosure, or shield.

A calorimetric experiment begins with the sample at a known temperature and in thermal equilibrium with its surroundings, the shield. A measured amount of energy is then added to the sample. The shield control system (controller) must act to re-establish thermal equilibrium between the sample and the shield within a reasonable length of time and in such a way that little, or no, heat is lost from the sample. After equilibrium is established, the temperature of the sample is again recorded. During equilibrium periods, the controller must supply enough heat to the shield to offset losses by conduction through its supporting structure and by radiation to the calorimeter jacket, which is maintained at some constant lower temperature by its contact with a thermal reservoir or constant temperature bath. During each period when the sample is heated, the shield requires additional heat in order to increase its temperature at a rate to match that of the sample.

In a typical system, a differential thermocouple is utilized to sense the sample-shield temperature error, thus providing information by which automatic regulation of the shield temperature is accomplished. The error signal is thus inherently a low level signal, which implies that the control system have high gain. To maximize sensitivity, it

is of importance to avoid electromechanical components and the inherent deadband which they induce into the control system and to maximize the gain, consistent with stability, with which the error signal is introduced into the control system.¹ The most convenient method of supplying and controlling the shield heat is electrical, such as by electronically controlling a current to a resistance heater on the shield.

Automatic thermal control devices fall into two categories:

(1) intermittently acting devices, such as a thermostat, and (2) continuously acting, or modulation, devices incorporated into a closed loop feedback system. The modulating type control action is preferred over the on-off action since the feedback path continually senses the effect of the manipulated variable, the shield current, on the equilibrium process. Electronic control action is commonly categorized into three processes, proportional, rate and reset, any combination of which may be incorporated into the design of a modulated shield heater current, control system.² Proportional control produces a heater current directly related to the magnitude of the input signal from the thermocouple. Automatic reset control is an integrating action which provides a floating correction proportional to the time duration as well as the magnitude of the error from the equilibrium set point. Rate control applies a correction proportional to the rate of change of the error signal and represents a differentiating action.

¹Davis, Elwood R. and Moiles, E. D., "Electronic Systems for Temperature Measurement and Control", Temperature - Its Measurement and Control in Science and Industry, v. III, p. 772-773, C. Herzfeld, ed. New York, Reinhold Publishing Corp., (1962).

²Ibid., p. 771-772.

This paper describes the design and operation of an all electronic, dc shield temperature regulator operating in the reset mode. The regulator operates as one element of a closed loop feedback system whose dynamic behavior is investigated using the analytical techniques of feedback control theory. The regulator is to be used in an adiabatic calorimeter employed in taking specific heat and electrocaloric measurements on ferroelectric crystals in the neighborhood of the ferroelectric transition.

II. CONTROLLER DESIGN AND PERFORMANCE

Since there is interaction between the various parts of the system, such as the shield, controller and the sample, the system must be treated as a whole in order to design a satisfactory controller. A simple, yet effective, tool for visualizing the behavior of a system is the block diagram. The blocks represent components, or component assemblies, whose physical behavior may be described mathematically by algebraic functions under static conditions and by integrodifferential equations under dynamic conditions. Figure 1 displays the pertinent variables and the interconnecting information streams of a closed loop temperature control system. Any difference between the set point signal and the output of the thermocouple is presented to the control system as an error signal. The output of the control system regulates the shield heater so as to correct for disturbances. The effect of this control action is sampled by the thermocouple sensor and fed-back for comparison with the set point, thus completing the feedback loop.

Since an equilibrium state for the system requires no control action other than the maintenance of a steady state value of current to the shield heater, which corresponds to a null or zero signal from the thermocouple, the two-input system may be reduced to a simpler one-input system, and rearranged as shown in Fig. 2. For proper control action, the error signal must be presented to the controller with the proper sign, as indicated in the diagram, so that the loop is representative of a negative feedback system. For example, if the

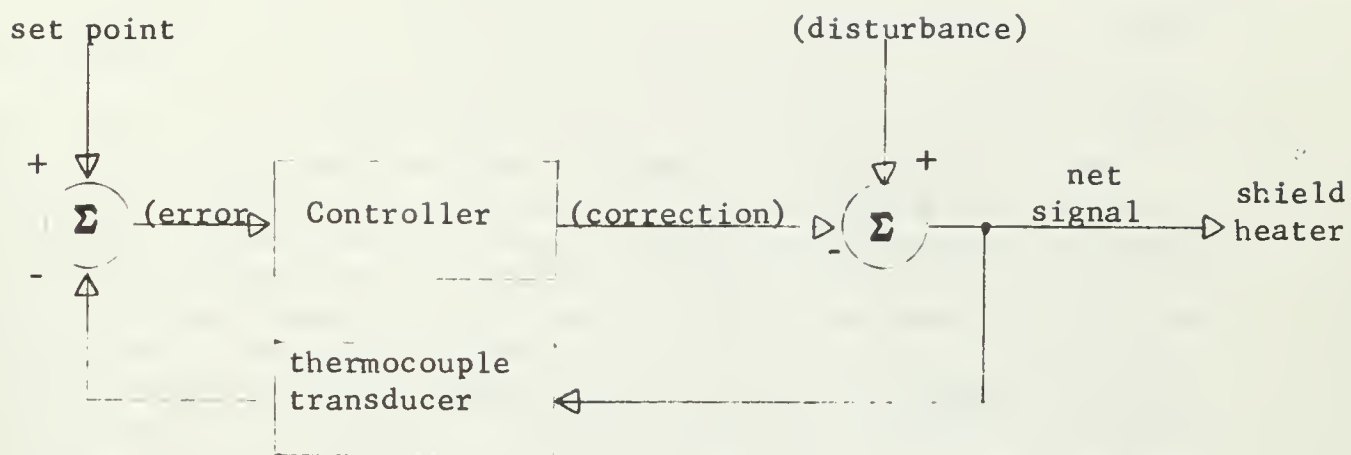


FIGURE 1. General Closed Loop Control System

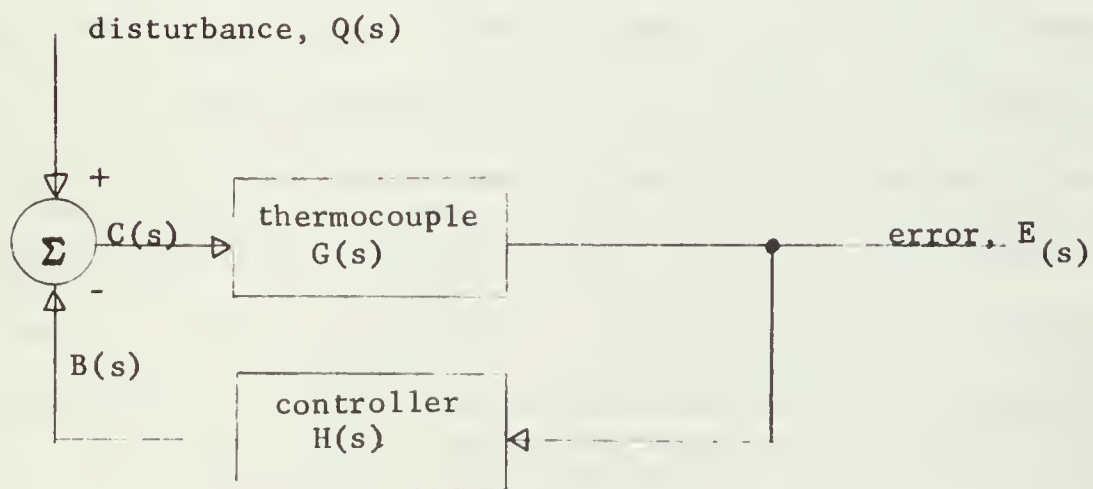


FIGURE 2. Single Input Closed Loop Control System with Laplace Notation

disturbance was such that the sample has just been heated,³ the polarity of the thermocouple signal must activate the controller to increase the heating current supplied to the shield heater so that the shield temperature may increase to match that of the sample.

For the controller discussed in this thesis, reset action was chosen as the method of control, instead of utilizing a combination of two or more types of control action, such as proportional plus rate or the more conventional use of proportional action by itself. An integrating type controller was chosen since a practical integrating device could be constructed simply and economically using solid state devices, and because the thermal lags associated with the typical adiabatic shield allows stability in the feedback loop to be achieved by a lag control network. The control action is accomplished by storing charge on a capacitor and modifying the charge stored by means of the error signal. The voltage appearing at the integrator output drives a current amplifier with the resistance heater on the shield for a load.

Several factors relative to the interaction between the controller and the calorimeter shield must be considered in order to obtain proper reset action. While a large integrator time constant permits disturbances of a long duration to be integrated without saturation of the integrator, a large time constant may inhibit control action, resulting in overdamping. A decrease of the time constant will result in increased hunting, and may also lead to loss of control. Preamplification of the error signal increases the sensitivity of the controller,

³ Heating of the sample and the measurement of its temperature are accomplished by separate, independent circuitry which is external to the thermal equilibrium feedback loop.

but too large a value of preamplification may cause increased hunting if the heater current is changed too quickly and too much. If thermal lags associated with the diffusion of heat through the shield are large enough, additional damping may not be necessary in the controller; while if they are not, damping may be added to the control system in the form of a compensation network. If system damping is larger than desired, the compensation network will take the form of a lead network to lessen the damping. If thermal lags are too large, the controller cannot be made to give a rapid response.

Thus, a simple reset action controller, composed of a preamplifier, a lead or lag compensation network, an integrator, and a current amplifier, behaves in a quantitatively complicated fashion. In designing the controller, the techniques of automatic control theory, to which the block diagram has provided a brief introduction, provide some insight into a qualitative design solution for the performance of the temperature controller in a system whose thermal constants are known. Final values of controller components may be selected after suitable operating experience has been obtained using the engineering estimates arrived at as a result of the control theory analysis.

It is easier to manipulate the Laplace transforms of the blocks in Fig. 2 than it is to work in the time domain. Thus, the following analysis uses the rules of transform algebra found in any standard text on automatic control theory.^{4,5} The two basic assumptions in the

⁴Clark, R. N., Introduction to Automatic Control Systems, Wiley, 1957.

⁵Van Valkenburg, M. E., Network Analysis, Prentice-Hall, 1955.

analysis are (1) the system elements can be described by lumped-parameters, as opposed to distributed parameters, and hence the system may be described by ordinary linear differential equations rather than partial differential equations whose transforms are more complex, and (2) the response functions of system elements are linear. Non-linear functions are linearized by assuming the function can be approximated by just the first-order term of its Taylor series expansion. With reference to Fig. 2, one can define the following quantities in transform notation:

- $G(s)$ is the thermocouple transfer function;
- $H(s)$ is the controller transfer function;
- $E(s)$ is the Laplace transform of the error, $e(t)$;
- $B(s)$ is the Laplace transform of the primary feedback signal, $b(t)$;
- $C(s)$ is the Laplace transform of the actuating signal, $c(t)$ and
- $Q(s)$ is the Laplace transform of the input disturbance, $q(t)$.

These variables are related by

$$\begin{aligned} E(s) &= G(s) \times C(s), \\ B(s) &= H(s) \times E(s), \\ C(s) &= Q(s) - B(s). \end{aligned}$$

These equations may be combined to eliminate $B(s)$ and $C(s)$,

$$\frac{E(s)}{Q(s)} = \frac{G(s)}{1 - G(s)H(s)} \equiv W(s)$$

where $W(s)$ is the system transfer function.

The thermocouple has a first order time constant response, since it is basically an energy storage element in series with a resistance to flow. The forward path transform has the following form:

$$G = \frac{c}{s + d}$$

The controller transform, H , of Fig. 2 is constructed from the transforms of the individual controller stages - preamplifier, compensation network, integrator and buffer/amplifier. A high gain preamplifier with adjustable gain, K_A , has a small time delay, $1/e$, in its response so that its transform is

$$G_A = \frac{eK_A}{s+e} .$$

A first-order phase lead compensation network has the form

$$G_c = \frac{s+a}{s+b} \quad \text{with } b > a$$

An ideal operational amplifier, which is used to construct an analog integrator, has gain, input impedance, and bandwidth which approach infinity and zero output impedance.⁶ Although real operational amplifiers have limitations, which complicate the form of the integrator transform, currently available, solid state, dc operational amplifiers have characteristics which approach the ideal so that the complete integrator transform may be approximated by a simple function,

$$G_I \approx -1/RC_s .$$

The buffer and current amplifier stages following the integrator have transforms which are pure gains taking the forms K_B and $-K_p$, respectively. If a stage does not load the previous stage, the complete controller transform can be written

$$H = G_A G_c G_I K_B (-K_p) = \frac{K(s+a)e}{s(s+b)}$$

with

$$K = K_A K_B K_p / RC \quad \text{sec}^{-1} .$$

⁶Tobey, G., "Analog Integration", Instruments and Control Systems, v. 42, p 49-50, January 1969.

The system transfer function may now be specified as

$$W = \frac{G}{1 + GH} = \frac{c(s+b)(s+e)s}{s^4 + (b+d+e)s^3 + (be+bd+de)s^2 + (bde + Kce)s + Kcea}$$

where, the open loop gain is given by

$$GH = \frac{Kec(s+a)}{s(s+b)(s+d)(s+e)},$$

and $1 + GH$ is defined to be the system characteristic equation. Figure 3 is a root locus plot of the characteristic equation which shows the loci of the roots in the s plane as the gain, K , increases from zero toward infinity. For $K = 0$ all the roots lie in the stable, left-half of the s plane. As K is increased toward infinity, the poles move toward the zeros (there are 3 zeros at minus infinity) along the dipole branches and the pole pair near the origin enters the complex plane as a conjugate pair. The imaginary axis is a region of marginal stability and the system will exhibit "ringing" at a critical value for K which places poles on this axis. From Fig. 3, one sees that oscillation will occur sooner for large K in a system with small thermal constants, c and d , than in a system in which the shield-thermocouple arrangement has a large thermal lag.

The system behavior is examined by applying a disturbance, Q , in the form of a step signal, T/s , and examining the resultant response,

$$E = QW = \frac{Tc(s+b)(s+e)}{s^4 + (b+d+e)s^3 + (bc+bd+de)s^2 + (bde + kce)s + Kcea}$$

The general procedure is to factor the denominator into four roots, expand E using partial fractions, solve for the residues and perform the inverse transform to the time domain with the aid of a table of

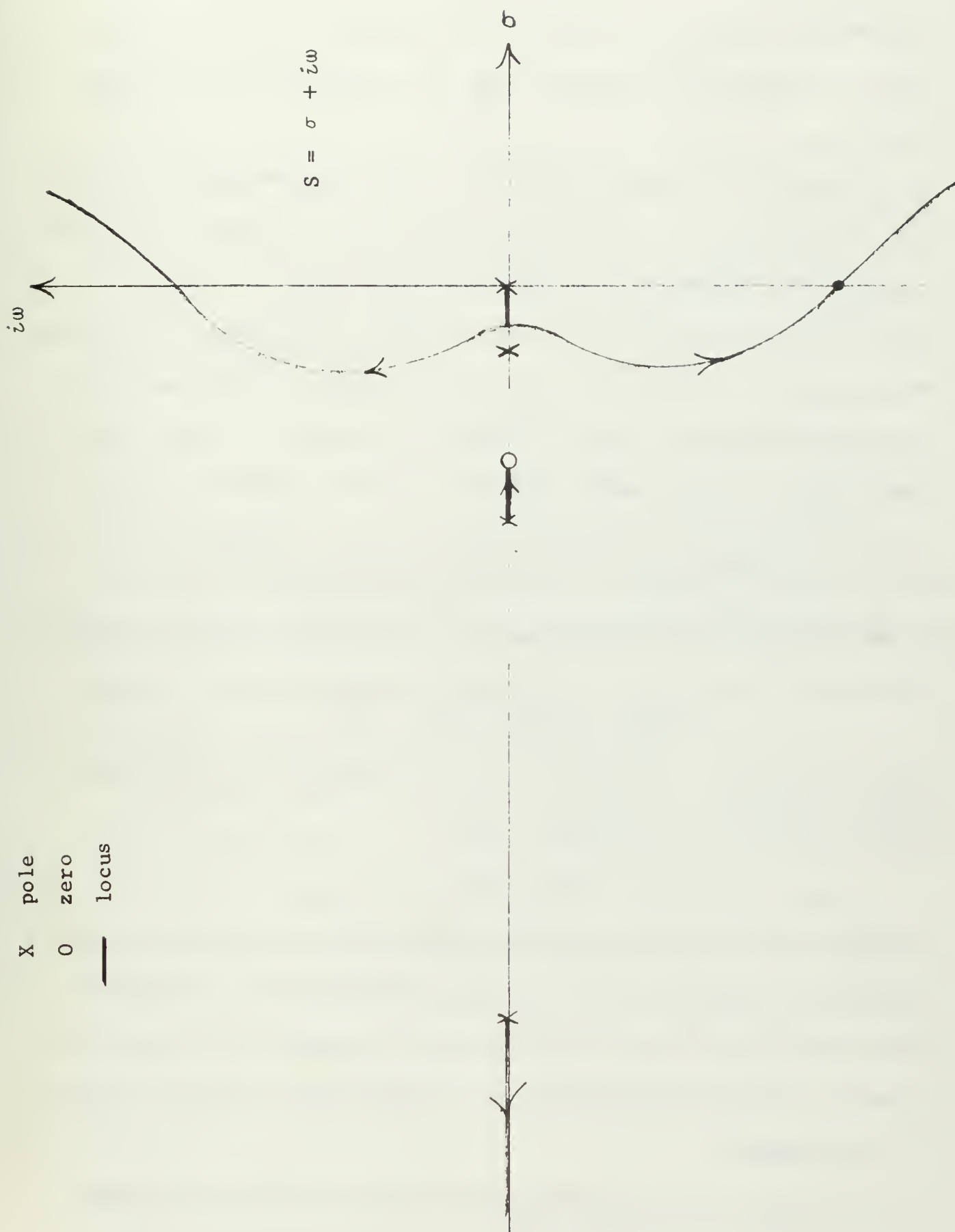


FIGURE 3. Loci of the Roots of the Characteristic Equation as a Function of K

Laplace transforms. The solution of the quartic with particular numerical coefficients is straightforward, albeit tedious,⁷ but it is too difficult to attempt for the general case. However, certain approximations may be made which reveal the nature of the solutions for two cases; K small, say $K \sim 10$, and large K in the region where ringing occurs.

For small K (and small s), the pole due to the preamplifier lag is considered 'remote' by virtue of its location in the remote part of the s plane. The residue at this pole is small compared to the other residues and, in addition, the time constant of this pole is very short when compared to the other time constants so that its contribution to the system behavior is negligibly small. For small K, with $G_A \sim K_A$ and $Q = T/s$, the error behaves like

$$\epsilon(t) \approx T \left\{ \frac{(2b - d)}{K} + \frac{c}{K}^{\frac{1}{2}} \sin[(kc)^{\frac{1}{2}}t + \pi] \right\} \exp[-t(b + d)/3].$$

At the output of the thermocouple, this equation has an initial value of

$$q(0) = K \epsilon(0) = T(2b - d)/3.$$

The disturbance is converged to zero, and since $q(0) = T$, by definition, there exists a requirement that

$$b \approx (d + 3)/2.$$

For large values of K, at large s, the pole of the pole-zero dipole branch is nearly cancelled by the zero and the residue of this pole becomes negligibly small. In this case, the compensation network has no effect, and the system behavior is characterized primarily by the

⁷ Burington, R. S., Handbook of Mathematical Tables and Formulas, pp. 7-9, Handbook Publishers, 1957.

remote pole and the conjugate pole pair. Shunting of the integrator input by a larger b/a ratio prevents extension of the compensation network to very high gains. No attempt was made to derive the general solution for $\epsilon(t)$; however, the error does converge to zero since the behavior of the system is the sum of a dying exponential from the remote pole and a sine term multiplied by a dying exponential from the conjugate pair. This behavior is valid until K is large enough to move the pole pair across the imaginary axis into the region of instability. An application of the Routh Criterion for stability⁸ shows the critical gain to be

$$K \approx \frac{d}{c} \epsilon$$

As K is increased beyond the critical value, the system nonlinearities assume a dominate role. At a high enough value of K , the system response will ultimately be bounded by a limit cycle operation describable by rapid shutoff. Thus, automatic shield control is accomplished through a combination of continuous and intermittent control as K is increased through several orders of magnitude.

Using the results of the previous analysis, construction of the controller proceeds in a straight-forward manner. For measuring and amplifying the output of the differential thermocouple, which is typically fractions of a microvolt, a Keithley model 149 millimicrovoltmeter was chosen. The model 149 is highly stable, has nanovolt sensitivity and contains built-in zero suppression to cancel spurious potentials generated along the thermocouple transmission line and at the amplifier input. The amplifier output drives the controller shown

⁸Van Valkenburg, op. cit., p. 417.

schematically in Fig. 4. As the discharge of the capacitor will normally be controlled by the input impedance of the buffer, it is then required that the leakage resistance of the capacitor exceed the input impedance of the buffer. This requirement can be met by a variety of capacitors. Since a large capacitance is necessary to produce a reasonable time constant, a tantalum capacitor was used. The capacitor may not be reduced with reduction compensated by an increase in R_3 , as the input current offset, drift and noise of the operational amplifier A_1 ⁹ are proportional to R_3 and these effects may become troublesome enough to require separate compensation if R_3 is further increased.¹⁰ The output stage can deliver 4W of continuous power to a load drawing 140 ma, when a heat sink is used with Q_2 . D_1 is a 10Ω temperature sensitive device which stabilizes Q_2 during sustained operations at higher currents.¹¹ The controller was mounted on a small etched circuit plug board. A standard 5 in x 19 in rack panel contains the controller, the necessary power supplies, an output current monitor, and a battery source for manually driving the controller. The input is Zener limited to a ± 10.2 volts to protect A_1 from overloading.

⁹Type μA 741, Fairchild Semiconductor, 313 Fairchild Drive, Mountain View, California.

¹⁰Weden, C. V., "Review of Operational Amplifier Principles," Application Bulletin - July 1966, Fairchild Instrumentation, 475 Ellis Street, Mountain View, California

¹¹"Sensitor", manufactured by Texas Instruments Inc., Post Office Box 5012, Dallas, Texas

The controller constants may be computed from the component values in Fig. 4. The output stage voltage gain, K_p , is derived using an approximate two parameter equivalent current.¹²

$$K_p = \frac{-h_{fe} R_L}{h_{ie} + (1 + h_{fe}) R_e} \approx \frac{-R_L}{h_{ie}/h_{fe} + R_e} = 1.8 \text{ for } R_L = 200\Omega$$

The transistor parameters were measured with a Tektronix Model 575 Curve Tracer, and found to be $h_{ie} \approx 17.5K$ and $h_{fe} \approx 175$. The buffer stage voltage gain expression is derived from the JFET equivalent circuit¹³ and the gain K_B , is computed using the transistor parameters given by the manufacturer's data sheet,

$$K_B = \frac{\mu R'_s}{r_d + R'_s(\mu + 1)} = 0.9 \text{ where } R'_s = R_s // [R_b + h_{ie} + (1 + h_{fe}) R_e].$$

The Keithley time constant was measured by observing the output voltage rise time to a step input on the 100 μV scale with a Tektronix model 454 CRO and found to be

$$1/e \approx 2 \text{ msec}$$

For the compensation network used

$$a = 1/R_1 C_1 = 1 \text{ sec}^{-1} \quad \text{and} \quad b = 1/(R_2 // R_1) = 1.2 \text{ sec}^{-1}.$$

If the thermal constants for a particular system are known, the idealized behavior for an assumed input may be predicted from $E = QW$. An examination of the orders of magnitude of the various terms in the

¹²Millman, J. and Halkias, C. C., Electronic Devices and Circuits, pp. 340-341, McGraw-Hill, 1967.

¹³Ibid., pp. 404-405.

Q1 TI 2N3819
 Q2 RCA 40361
 $\frac{1}{2}W$ 5% carbon resistors
 15 DCWV 10% capacitors

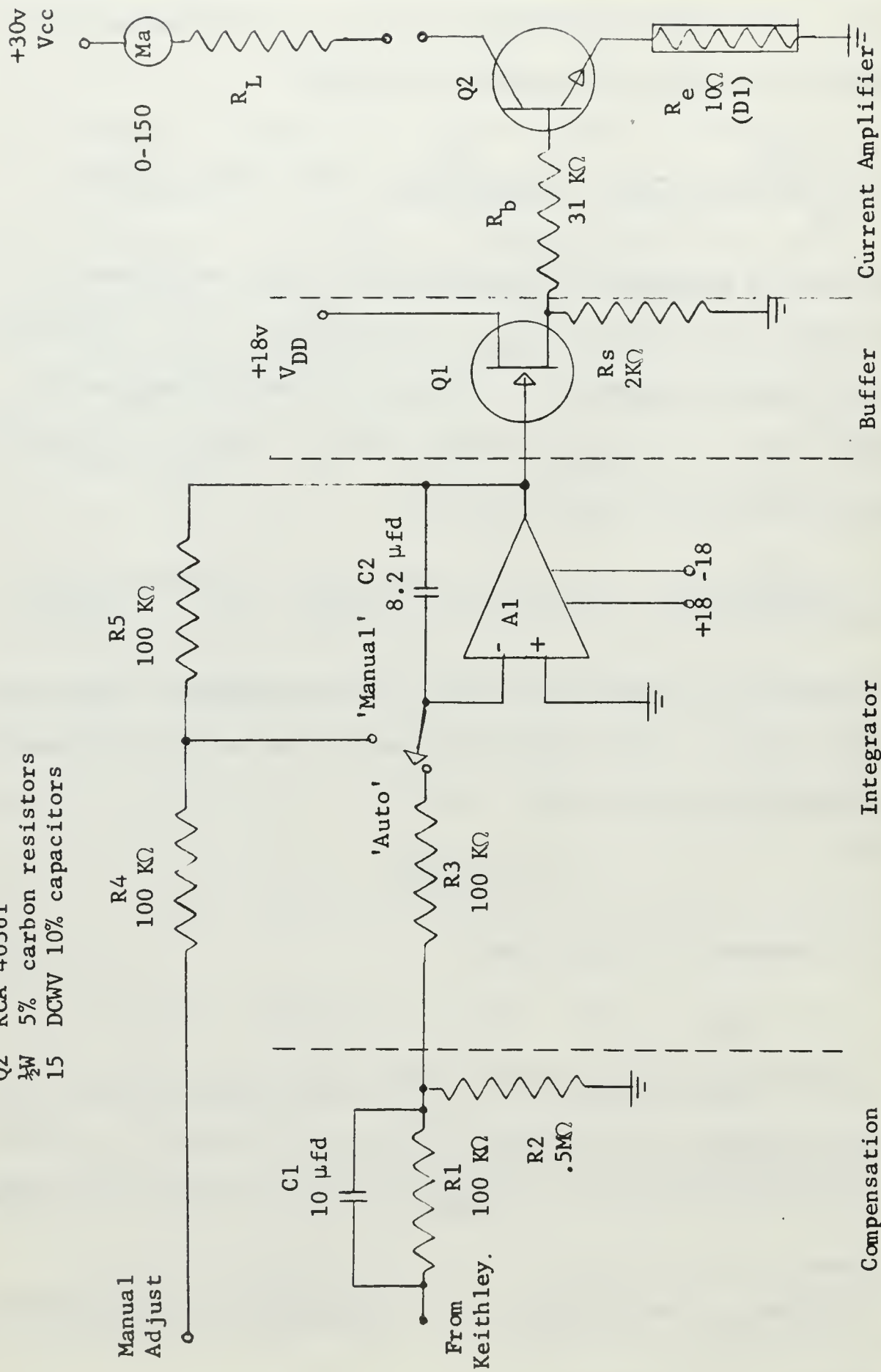


FIGURE 4. Controller Circuit Diagram

transfer function reveals which element(s) of the controller dominates its behavior for a given gain. The critical gain for stability of the system can only be calculated if the thermal delays of the calorimeter are specified.

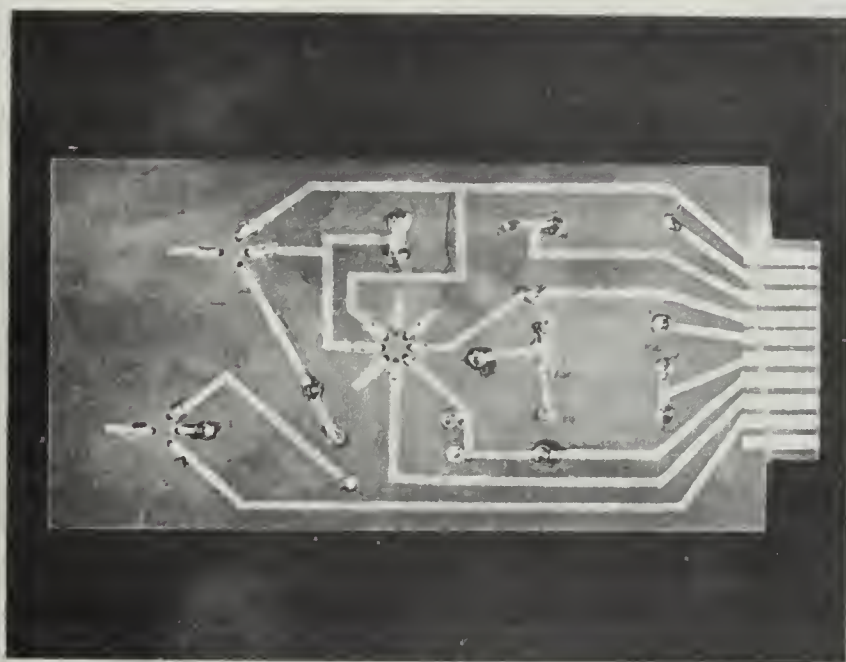


FIGURE 5. Controller Etched Circuit Board

III. RESULTS

The controller was tested with two calorimeters of very different thermal design. The first calorimeter, for which the most extensive testing was carried out, was for use near 120°K and was characterized by sluggish thermal response. The second, a developmental calorimeter, was designed for use near room temperature and was characterized by very small thermal time constants.

The lower temperature calorimeter contained a cylindrical Cu shield, with dimensions 2.0 in o.d. x 0.016 in wall x $4\frac{3}{16}$ in length, and mass of 98.7 gms. The shield was isolated from the calorimeter jacket by a cylindrical Cu furnace with dimensions, $2\frac{1}{8}$ in i.d. x 0.002 in wall x $4\frac{11}{16}$ in length, and mass of 38 gms. Both cylinders screwed onto a 47 gm Cu lid which was silver brazed to a $\frac{1}{2}$ in i.d. 0.01 in stainless-steel tube 8.5 cm long. The entire assembly was sealed within a vacuum jacket which, in turn, was immersed in a bath of liquid nitrogen. The heater consisted on an 80 Ω manganin coil around the lid stem in series with a 27 Ω manganin coil around the outside surface of the furnace cylinder so that most of the heat appeared at the lid. Current distribution between the two heater coils was externally controlled by a potentiometer to trim gradients and the entire heater assembly appeared as a 200 Ω load at the controller terminals. The thin walled stainless-steel tube was characterized by a thermal resistance,

$$R_{th} \equiv \Delta T / \dot{Q} = \ell / AK = 625 \text{ }^{\circ}\text{K/w}$$

where $K_{ss} = 0.17 \text{ W/cm} \cdot ^\circ\text{K}$. At $T \approx 120^\circ\text{K}$ radiation was relatively small.^{14, 15}

The thermal lag of the calorimeter appears in the system transfer function of the previous chapter through G , the thermocouple transfer function, which is determined experimentally. The testing technique measures the transient response of the thermocouple by comparing the measured temperature reading to a theoretical ramp change in temperature produced by imposing a step change in current through the shield heater under adiabatic conditions.¹⁶ Neglecting the IR drop at the thermocouple-shield junction, the calorimeter tested had time constants given approximately by

$$1/\tau \approx 6 \text{ sec} \quad \text{and} \quad 1/d \approx 3 \text{ sec.}$$

These constants are for a 0.002 in diam chromel-alumel thermocouple bonded to the shield with GE7031 varnish. When these values are inserted into the previous theory for $\epsilon(t)$, the maximum allowable gain for continuous control action is

$$K_A \approx 10^3$$

Since this thermocouple produces an average of $15\mu\text{V}$ per degree of

¹⁴Reese, W. and May, L. F., Phys. Rev. 162, 512 (1967).

¹⁵Reese, W. and May, L. F., Laboratory Notebook, January 1966 - June 1967, Naval Postgraduate School, Monterey, California 93940, unpublished.

¹⁶Green, S. J. and Hunt, E. W., "Accuracy and Response of the Thermocouples for Surface and Fluid Temperature Measurements," Temperature-Its Measurement and Control in Science and Industry, pp. 708-711.

differential, the Keithley should be operated on the $1\text{ }\mu\text{V}$ scale where $K_A = 10^7$ for maximum sensitivity. At this value of K_A , full scale ringing occurred and the controller entered a limit cycle. However, the performance of the controller on the $1\text{ }\mu\text{V}$ scale, as measured by the thermal response of the sample, was acceptable as shown in Fig. 6 and was an improvement over a proportional controller which was previously used with this calorimeter.¹⁷

For too large a sample heating step, corresponding to coarsely spaced data points, the controller applied maximum available power initiating an extended limit cycle observed as an overshoot on the sample recording. The maximum sample heating step was experimentally determined and depended on several factors; for example, the current gain of the output stage, the heat capacity of the sample and the proximity of the thermocouple junction to the sample heater.

Drift of the sample temperature for the sample used to obtain Fig. 6 at a point about 5°K below the ferroelectric anomaly was improved from 0.045°K/hr to 0.006°K/hr , measured over a 9 hour period, after a few minutes of careful adjustment of the Keithley zero suppress.

The controller was less satisfactory for the second calorimetric system. The second system was characterized by a light mass Al construction and coupling to the bath was by a short brass link with $R_{th} = 8.3^\circ\text{K/W}$. In addition, radiation coupling of the shield to the bath was much more important ($\propto T^3$) as was the increased coupling of the sample to the shield. The constants, c and d , were not determined for this calorimeter but the time response was at least a factor of 10

¹⁷ Reese and May, Phys. Rev. 162, 612 (1967).



*The vertical scale represents temperature increase and the horizontal scale shows elapsed time with 50 sec between divisions

FIGURE. 6. Sample Trace of Temperature Versus Time Illustrating Equilibrium of Potassium Dihydrogen Phosphate for a .025°K Step Beginning at $T = 118.151^{\circ}\text{K}$.

faster. A sample recording exhibited unsatisfactory oscillations tracable to the ringing of the thermocouple signal. The trace oscillations were minimized, but not entirely eliminated, by reducing the integrator time constant by a factor of 10, limiting the maximum current delivered to the load and reducing the gain, K_A . Despite these changes the system still performed only marginally; however, the system could be used to accrue data.

To overcome this problem, a proportional control stage was added and a second controller was assembled which operated in both the reset and proportional modes. The test circuit is shown in Fig. 7 with approximate component values. This network has exhibited extremely good stability with the Cu calorimeter. Control action was so positive that the thermocouple error never exceeded $2 \mu V$ during sustained sample heating under maximum power. The performance of this controller in the second system was an improvement over the reset action controller; however, the sensitivity of the calorimeter still exceeded the ability of the controller to eliminate hunting on the sample trace at the required gain level of $K_A = 10^7$ under all conditions, although stable operation was obtained with $K_A = 3.3 \times 10^6$.



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BIBLIOGRAPHY

1. Davis, E. T. and Moiles, E. D., "Electric Systems for Temperature Measurement and Control", Vol III, Part 2 of Temperature-Its Measurement and Control in Science and Industry, Charles Herzfeld, Editor, 3 vols., New York, Reinhold Publishing Corp., 1962.
2. Clark, R. N., Introduction to Automatic Control Systems, Wiley, 1957.
3. Van Valkenburg, M. E., Network Analysis, Prentice Hall, 1955.
4. Tobey, G., "Analog Integration," Instruments and Control Systems, v. 42, January 1969.
5. Burington, R. S., Handbook of Mathematical Tables and Formulas, Handbook Publishers, 1957.
6. Weden, C. V., "Review of Operational Amplifier Principles," Application Bulletin-July 1966, Fairchild Instrumentation, Mountain View, California.
7. Millman, J. and Halkias, C. C., Electronic Devices and Circuits, McGraw-Hill, 1967.
8. Reese, W. and May, L. F., The Physical Review, 162, 1967.
9. Reese, W. and May, L. F., Laboratory Notebook January 1966 - June 1967, Naval Postgraduate School, Monterey, California.
10. Green, S. J. and Hunt, T. W., "Accuracy and Response of Thermo-couple for Surface and Fluid Temperature Measurements," Vol. III, Part 2 of Temperature-Its Measurement and Control in Science and Industry, Charles Herzfeld, ed., 3 vols. New York, Reinhold, 1962.

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13. ABSTRACT

An automatic, electronic controller was designed for use with adiabatic calorimeters. The controller employed reset action, and its behavior at different system gains was analyzed using the analytic techniques of feedback control theory. In accord with the analysis satisfactory performance was obtained with a calorimeter characterized by large thermal lags, but marginal performance was obtained with another calorimeter characterized by a rapid thermal response. A second controller, which employs reset and proportional action gave satisfactory results during preliminary testing for both calorimeters.

<div>14</div> <div>KEY WORDS</div>	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
<div>adiabatic calorimeters</div> <div>feedback control theory</div>						

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